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Measurement and analysis of machining induced tribological characteristics in dual jet minimum quantity lubrication assisted turning of duplex stainless steel

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ABSTRACT

In this work, the sustainable machining approach is promoted by implementing the dry and minimum quantity lubrication (MQL) cooling conditions in the turning of duplex stainless steel. Initially, the turning experiments were performed under dry as well as MQL conditions and then, the influence of different positions of MQL nozzles on tribological and machining performance of 2205 duplex steel was investigated. The cutting parameters were kept fixed and the performance is evaluated in terms of surface roughness, micro-hardness, energy consumption, tool wear, machined surface microstructure and chips morphology. The results demonstrated that the highest average surface roughness values were obtained under dry conditions, with a value of 2.20 μm while MQL (flank + rake directions) produces the lowest surface roughness value of 1.55 μm with an improvement of 30%. Moreover, dual-jet MQL gives the lowest energy consumption (229 kJ) and tool wear (0.15 mm) with 23.67% and 52.38% enhancement, respectively.

1. Introduction

Stainless steel has many superior characteristics such as higher strength, corrosion resistance, higher hardness, ductility, rigidity, and heat resistance [1,2]. In comparison to 304 and 316 stainless steels, duplex stainless steel is more corrosion resistance due to the presence of chemical constituents like nickel, chromium and molybdenum etc. Duplex stainless steels with ferrite and austenite structures are a highly preferred type of stainless steel in recent years. The ferrite structure in this steel increases its resistance against mechanical and stress corrosion cracking, while the austenite structure increases corrosion resistance and ductility. Due to these properties, it is used in many areas such as petrochemical, mining, liquefied nature gas, nuclear power, oil and gas sectors etc. and it's mostly used in thin-sectioned parts provides an advantage over other stainless steels [3,4]. Stainless steels are a group of materials known as a difficult to machine materials [5,6]. In the machining of these steels, especially with the effect of friction, excessive wear occurs on the cutting tool [7,8]. During the machining of these materials, chip accumulation (BUE) and continuous chip formation occurs on the cutting edge, which significantly affects the machinability [9,10]. Another problem is the deformation hardening caused by the thermo-mechanical effect that occurs during machining. This deformation hardening affects the chip formation and causes vibration during machining. Thus, the surface integrity in terms of surface roughness and residual stresses of the workpiece is highly affected [11]. By using more rigid cutting tools and machine tools in the machining of stainless steels, vibrations generated during machining can be prevented. Due to the high alloying elements and austenite structure in stainless steels, hard and continuous chips are formed, therefore it is recommended to be processed with high wear-resistant carbide cutting tools with chip breakers. Low feed and cutting speeds are recommended to prevent deformation hardening during cutting [12–14]. Carbide cutting tools have more strength than most of the cutting tools. However, carbide cutting tools have disadvantages such as brittleness and low shock

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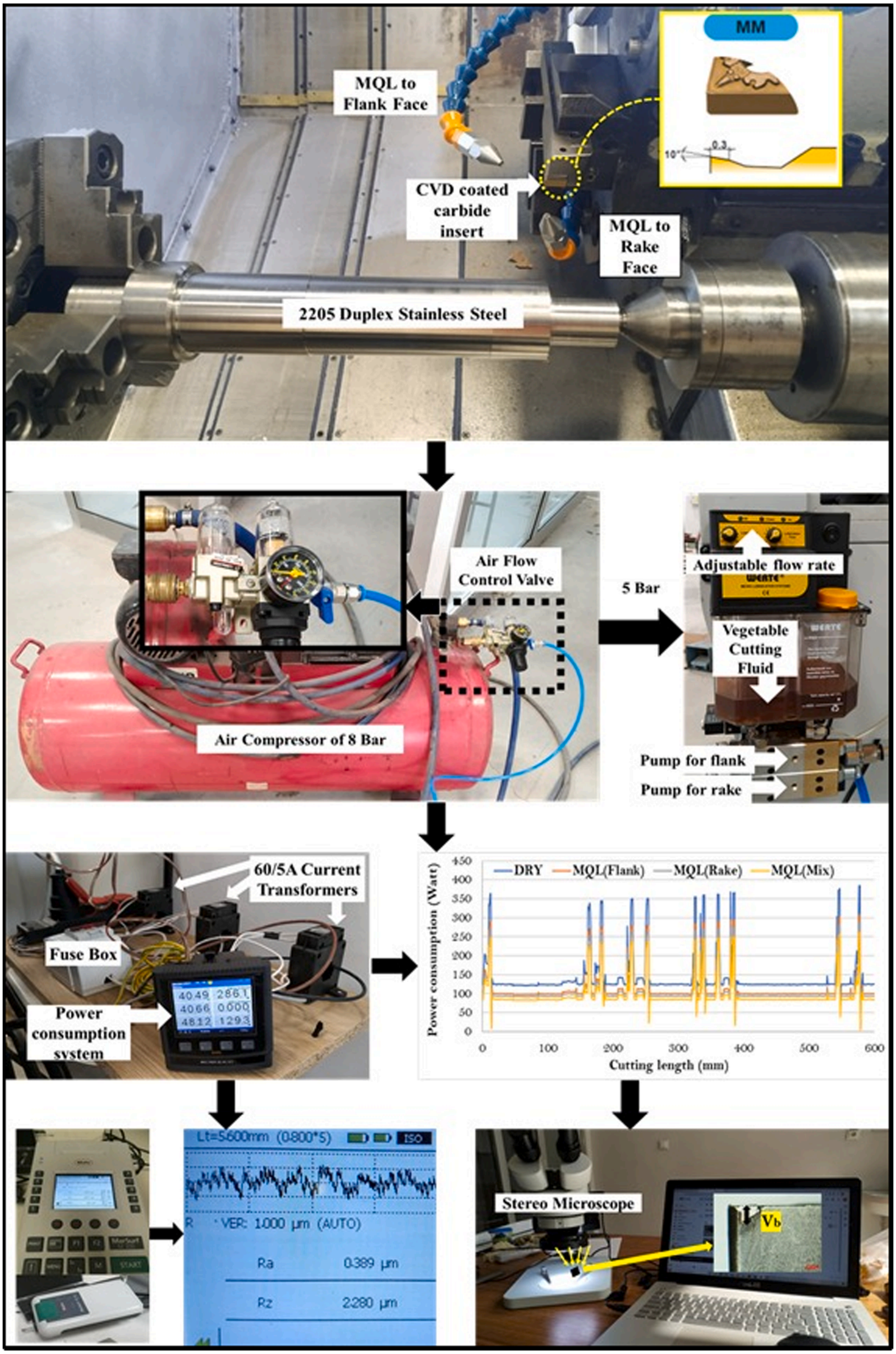


Fig. 1. Experimental setup used in this work.

resistance. Titanium and tantalum are added to overcome these limitations of carbide cutting tools [15,16]. Cemented carbide is a powder metallurgy product, mainly produced from different carbides (WC, TiC, TaC or NbC) in binder (Co). They are used in the machining of materials that are difficult to machine due to their strong chemical stability, high compressive strength, high hardness, good hardness at high temperatures, good abrasion resistance, high thermal conductivity, high modulus of elasticity. Also, Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD) coating types can be applied to cemented carbide tools for eliminating the deficiencies of uncoated tools [17].

Besides, the application of metal cutting fluids provide a good improvement in the life of cutting tools and surface roughness of the workpieces [18,19] with decreasing heat and friction in the cutting zone

Table 1
Design and technical aspects.

Classification	Description	Value			
Werte STN15 MQL device	Working air pressure	5 bar			
	Flow rate	100 ml/h			
WerteMist lubricant	Chemical compound	Triethanolamine			
	pH	8.2			
	Viscosity	$300*10^{-6}$ m^2/s			
	Thermal conductivity	0.15 W/m K			
Cutting parameters	Cutting speed	200 m/min			
	Feed rate	0.2 mm/rev			
	Depth of cut	1 mm			
	Flow rate	100 ml/h			
	Cutting environments	Dry	MQL1 (Rake)	MQL2 (Flank)	MQL3 (Mix)

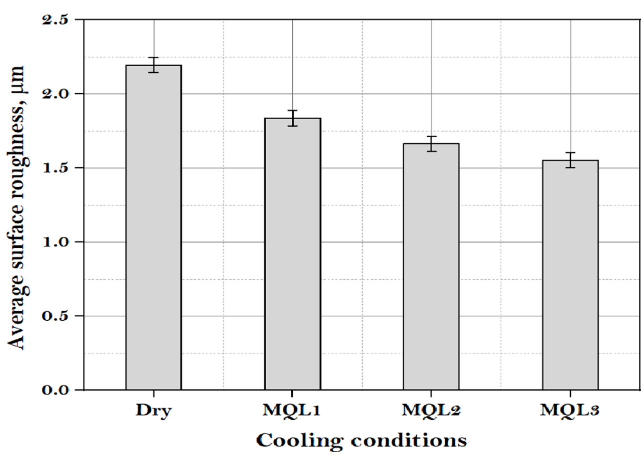


Fig. 2. Average surface roughness in different cutting environments after 3000 mm cutting length.

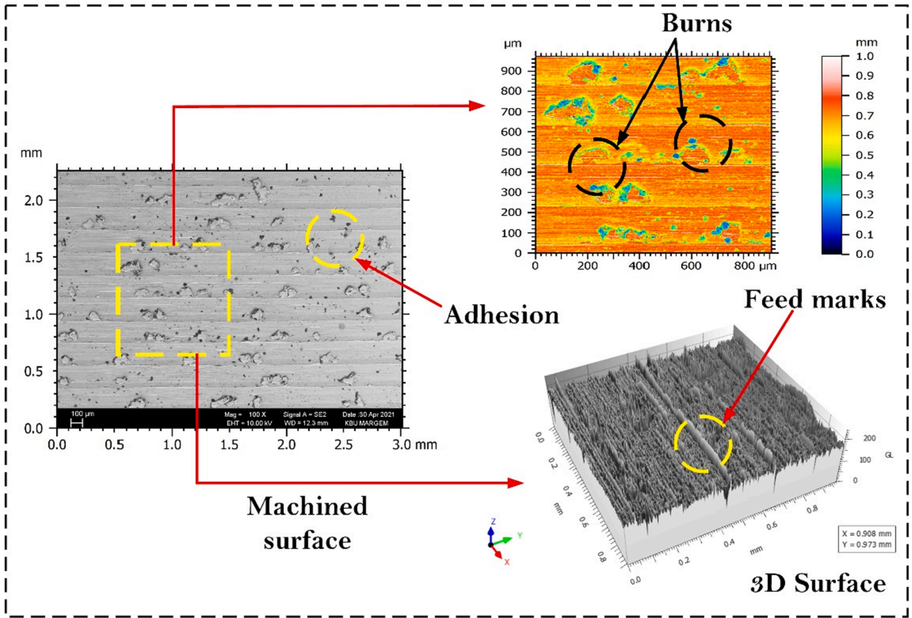
[20,21]. Moreover, the cutting fluids provide the dimensional precision by reducing the residual stresses with their cooling/lubricating feature [22]. Generally, the cutting fluids with their lubrication functions create a boundary layer in the cutting zone, and as a result the quality of the surface roughness as well as tool life increased [23,24]. However, the cutting fluids used are harmful for environment and operator of the machine. Therefore, there is a need to implement sustainable cooling methods to reduce the cost as well as harmful effect on environment [25,26]. Several cooling strategies such as cold air, cryogenic cooling, MQL, vegetable oil are used in chip removal processes [1,27–30]. These cooling techniques enhance the machining behavior and the sustainability of machining operations [31–33]. Till now, MQL system is highly recommended and used for machining difficult to machine materials like titanium, nickel-based alloys, steels etc [34]. Further, the positioning and direction of MQL nozzles plays a prominent character to enhance the machinability behavior of different materials [35]. Eventually, it is admirable to remark that the effectiveness of any cooling system was decided by its mode of direction, position, type of cutting fluid used etc [36]. Many research efforts were performed on the effectiveness of MQL system. Mia and Dhar investigated the influence of MQL nozzle positions in turning of Ti6Al4V alloy and found that duplex nozzles are more efficient in lubrication and cooling than single nozzle [37,38]. Sohrabpoor et al. combined the nozzle directions to the rake and flank face of the inserts in MQL turning of AISI 4340 steel. The authors observed that it is generally more efficient method than spraying of lubricant [39]. Kaynak et al. [40] compared the cutting environments in machining of NiTi shape memory alloys and emphasized that MQL method is obviously better than dry conditions in terms of surface roughness, cutting force and tool wear conditions. Gajrani [41] studied on the performance of carbide cutting tool under different cooling conditions in turning of Ti6Al4V alloys. The author underlined that MQL method is greener and clearer than dry conditions under the same cutting parameters. Zhu et al. [42] investigated the superiority of MQL lubrication method over the dry condition in machining of Aluminum 2024-T351 alloy. The researchers found that MQL method is clearly better than dry condition in terms of cutting temperature and tool wear. Bonfa et al. [43] compared the directional effect of MQL in machining of D6 steel by PCBN insert. They investigated that the application of MQL on rake face reduces the tool wear upto 10% as compared with MQL on flank face. Moreover, MQL has eco-friendlier effect than dry condition in terms of the surface quality and tool life. Touggui et al. [44] researched the machinability of AISI 304 stainless steel during machining with WC inserts under dry and MQL techniques. As a result, MQL has superior performance than the dry turning conditions.

The above-mentioned studies clearly mentioned that the sustainable cooling conditions like MQL is beneficial for machining different materials. The literature studies are commonly based on single or dual channel, but single jet to rake or flank face of the inserts. The influence of different nozzle positions of MQL (dual-jet) on machining performance of duplex steel has not been reported in relevant literature. In our study, the mechanism of MQL is dual-channel having also both single and dual jets since the direction of MQL spray mode is very prominent parameter and the machining as well as tribological performance is highly dependent on it. Therefore, this paper reports the improvements in tribological and machining performance of 2205 Duplex Stainless Steel under two-Directional MQL system. The comparison in terms of tool wear, surface roughness, energy consumption, machined surface microstructure and chips morphology was also made under dry, and MQL with different spray mode of nozzles.

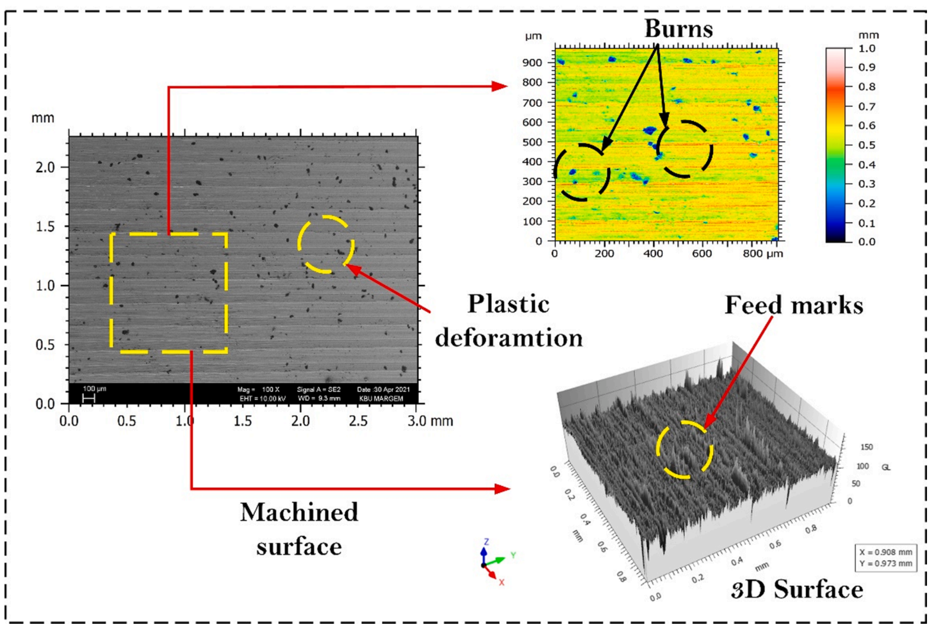
2. Materials and methods

2.1. Details of material, cutting tool, machine tool and cooling system

The workpiece material utilized in the experiments were 2205 duplex stainless steel having the dimensions of 50x250 mm and the hardness of 30 HRC. The main elements of workpiece are as nickel, chromium and molybdenum with the percentages of ~5.5%, ~22% and ~3.0%, respectively. The coated cemented carbide cutting tools (manufactured by Mitsubishi) was used for machining tests. The ISO designation of cutting tools were CNMG 120408 MM MC7025. The machining parameters are intermediate parameters suggested by Mitsubishi cutting Tool Company. Fig. 1 shows the geometry of the cutting tools, designated by the MM chip breaker. CVD coating quality is denoted by the code MC7025. The machining trials were performed on Taksan TTC-630″ CNC setup including a 15 kW spindle and Fanuc operating system etc. The Werte lubrication setup manufactured by SBH Company (Istanbul, Turkey) was used for MQL system. The manufacturer installed the extra air pump to deliver the cutting fluid (WerteMist) from the two positions. Tables 1 provides the characteristics of Werte STN15 and WerteMist lubricant based on hazardless Triethanolamine [45,46]. The WerteMist is a special lubricant having a feature of volatile. The optimum air pressure of 5 bar and flow rate of 100 ml/h was used for turning experiments. These values were recommended by MQL manufacturer but these values could be easily adjusted with air flow regulator and PLC control unit install in the MQL system. Further, the MQL was delivered at three positions i.e., MQL1 (rake face, 100 ml/h), MQL2 (flank face, 100 ml/h) and MQL 3 (rake, 50 ml/h + flank face, 50 ml/h) and the flow rate was kept same, as supported by literature review [47,48]. The nozzle tips of the rake and flank sides are both located at 45 mm distance apart and at a 45° angle to the tool nose [49]. Further, the cutting parameters are intermediate parameters suggested by Mitsubishi cutting Tool Company. Table 1 also shows the cutting settings for the turning



(a)



(b)

Fig. 3. SEM images of machined surfaces after 3000 mm cutting length, (a) Dry condition (b) MQL1 (Rake) condition, (c) MQL2 (Flank) condition and (d) MQL3 (Rake and flank) condition.

trials, which include cutting parameters and also four cutting environments.

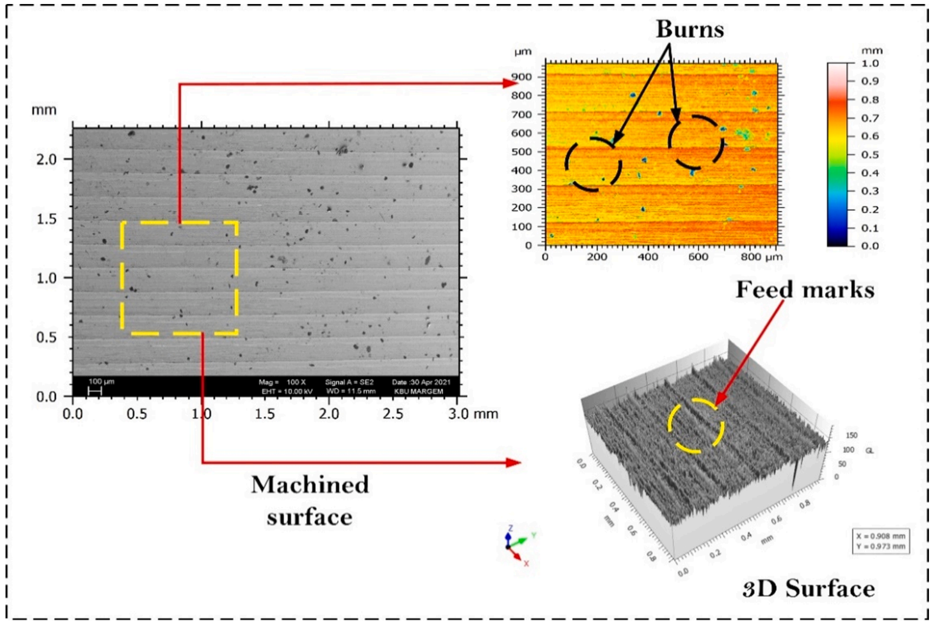
2.2. Machining of responses

In this work, the surface roughness, energy consumption, tool wear, micro-structure and micro-hardenss values were measured. Fig. 1 also shows the measurement of power consumption in dry and MQL conditions using a KAEL Network Analyser (Istanbul, Turkey). This instrument is highly precised to measure power at different stages of CNC machining because three 60/5A current transformers were managed to measure the power. Then, the energy consumption from power consumption was calculated with the help of Eq. (1) and (2).

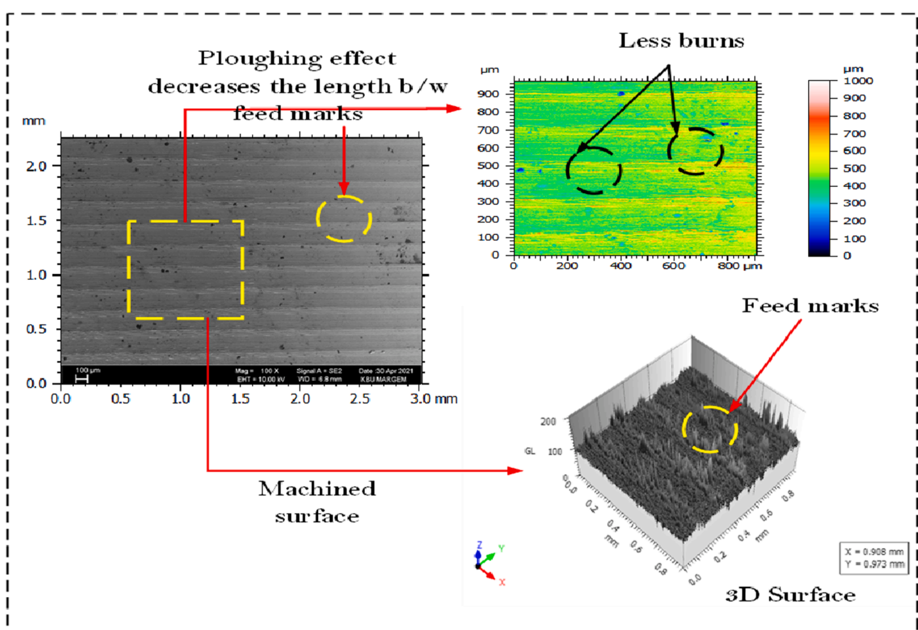
$$Energy = Power^{*}\left(\frac{L}{f^{*}N}\right) \tag{1}$$

$$N = \frac{1000^{*}V}{\pi^{*}D} \tag{2}$$

where L is demonstrated as length of cut in mm, f is feed rate in mm/rev,



(c)



(d)

Fig. 3. (*continued*).

N is Rpm, V is cutting speed in m/min, and D is diameter of wokrpiece in mm. Then, the average surface roughnesses (Ra) for each condition was measured using a Mahr M300 surface harshness profilometer. The four surface roughness measurements were collected by rotating the workpiece to 90° and then taking an arithmetic average of the results. Similarly, the tool wear images were taken using a Huamao stereo microscope with same magnifications. These values were measured for all stages of a 3000 mm cutting length and then the ISO standard 3685 for tool wear i.e., wear rate of Vb 0.3 mm was compared. These values were measured 3 times and the average was considered for analysis purpose. Then, the worn tools, separated chips and machined surfaces after a 3000 mm cutting length for each cutting environments were examined with scanning electron microscope (SEM). The chemical composition of the cutting zone was determined using an Energy Dispersive X-Ray (EDX) Spectrometer of the chips and inserts. Lastly, the microstructures and microhardness of machined surface for each cutting environment were analyzed. The specimens were initally cut and embedded in a bakelite and then, the specimens were grinded with 600, 800, 1200 and 2500 sandpapers followed by etching process (3 ml HNO3 + 1 ml HCl by immersed in it during 30 min) for microstructure analysis, respectively. The microstructure of the machined surfaces were analyzed by Nikon Eclipse MA200 inverted microscope. After microstructure analysis, the

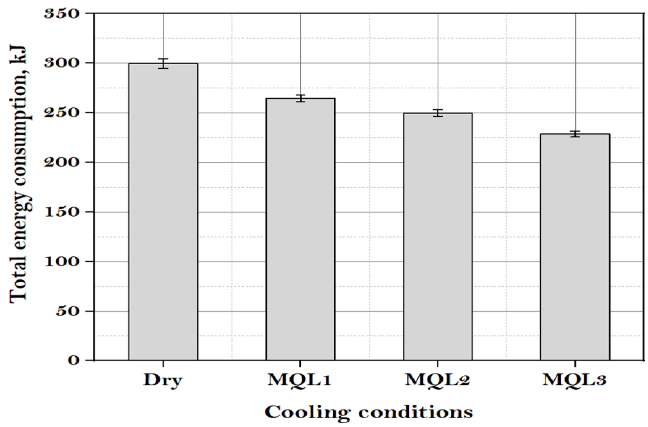


Fig. 4. Energy consumption in different cutting environments.

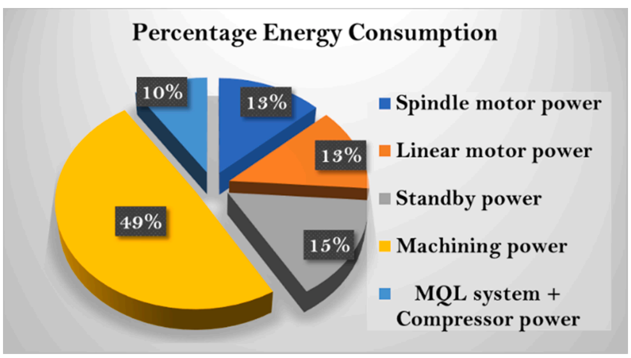


Fig. 5. The percentage energy consumption for a simple machining test.

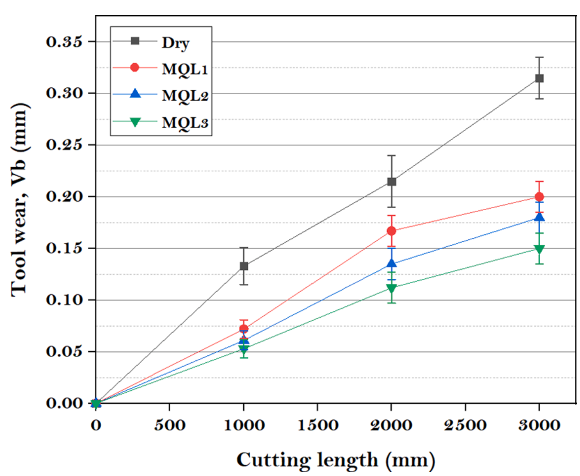


Fig. 6. Tool wear under different cutting environments.

microhardness of the materials was determined via QNESS Q10 A + Microhardness tester by HV1 (1 kgf) as Vicker hardness.

3. Results and discussion

3.1. Evaluation of surface roughness

After the machining process, the workpiece is expected to be within the desired size and tolerance values and average surface roughness expression is mostly used to indicate the overall quality of the surface. As the average surface roughness value decreases, the surface quality improves. Fig. 2 shows the average surface roughness variations in different cutting environments, whereas the SEM and 3d surface of machined surfaces are shown in Fig. 3. Recent stuides confirms that the application of MQL gives the better results in terms of good surface quality as indicated in work of Abas et al. [50], Gaurav et al. [51], Yıldırım et al. [52] and Marques et al. [53]. Abas et al. [50] analyzed the effect of MQL from rake face in turning of 6026-T9 aluminum alloy. Gaurav et al. [51] also studied the influence of MQL from rake face in machining of Ti-6Al-4V alloys. Yıldırım et al. [52] examined the machining performance of 625 nickel alloy with coated carbide inserts in MQL from rake face. From all the studies mentioned, the authors pointed out that the surface quality upto 30%, 25%, 20% is improved under MQL conditions, respectively. As a result, the sprayed lubricants in MQL technique ensure protection of the films in the contact area of the tool and workpiece by reducing the friction coefficient (CoF). [54]. On the other hand, Marques et al. [53] also studied the influence of MQL from flank face in turning of Inconel 718 alloy. They indicated that there is also an enhancement in surface quality by decreasing the average surface roughness values about 35% while using MQL conditions. The mentioned studies showed that the direction of the MQL nozzles are important in improvement of surface quality during the machining of modern materials. In the current study, the cutting environments were selected as dry, MQL to rake (MQL1), MQL to flank (MQL2), and MQL to both flank and rake (MQL3) face. At the constant cutting parameters, MQL 1 conditions show better surface quality upto 16.3% than dry conditions. Moreover, MQL2 conditions are better than MQL1 and dry condition as 9.43% and 24.2%, respectively. This is because the because the cutting depth is much larger than the tool nose radii. That means the cutting fluid will be completely penetrate into the workpiece, and so more effected from flank face rather than rake face. However, by comparing of all cutting environments, MQL3 achieved the best surface quality because of more durable protective film prdocued at the tool-workpiece contact area. The concept of this film is clearly mentioned in EDX analysis, as shown in Fig. 8b,c,d. According to the experimental results, the highest average surface roughness was obtained under dry conditions with the value of 2.20 μm. On the contrary, the MQl3 ocndition produce lowest surface roughness value of 1.55 μm followed by MQL 1 (1.84 μm) and MQL 2 (1.66 μm), respectively. MQL3, especially sprayed from both faces are more efficient on Ra values and as a results, good surfacae finish was observed. This mechanism is also supported by the burning effects produced under different cooling conditions while turning of duplex steel, as shown in Fig. 3. It is supported by the penetration of volatile lubricants used in MQL technique into the cutting area auxiliary by decreasing the friction between tool and workpiece [55]. Moreover, the MQL3 have strong cooling as well as lurbicating effect with the applcaition of compressed air and cutting fluid, and this phenomena results in good cushioning effect between tool and work piece. Consequently, the less vibrations are generated and the surface quality is improved with MQL3 condition. One more phenomena is attributed to this dual jet mechanism is that the cutting fluid on rake face and flank face tends to reduce the built-up-edge (BUE) formation at cutting tool with imrpovised tribological characteristics in terms of less adhesion, less plastic deformation of material, good surface finish, less tool wear, easily removal of chips etc.

3.2. Energy consumption analysis

CNC machine tool has several operational elements, namely spindle system, linear drive system and standby system. Spindle rotor initiates the rotational movement of tool/workpiece, the feed motor offers a linear or rotary movement, the hydraulic system delivers the holding force and feed drive, and the tool arm motor mechanically differ the cutting tool. Moreover, the cooling system and its accessories also consumes some power and energy during machining operation. The present work deals with the application of MQL system and thus, the power used to operate air compressor and MQL system is also considered for analysis

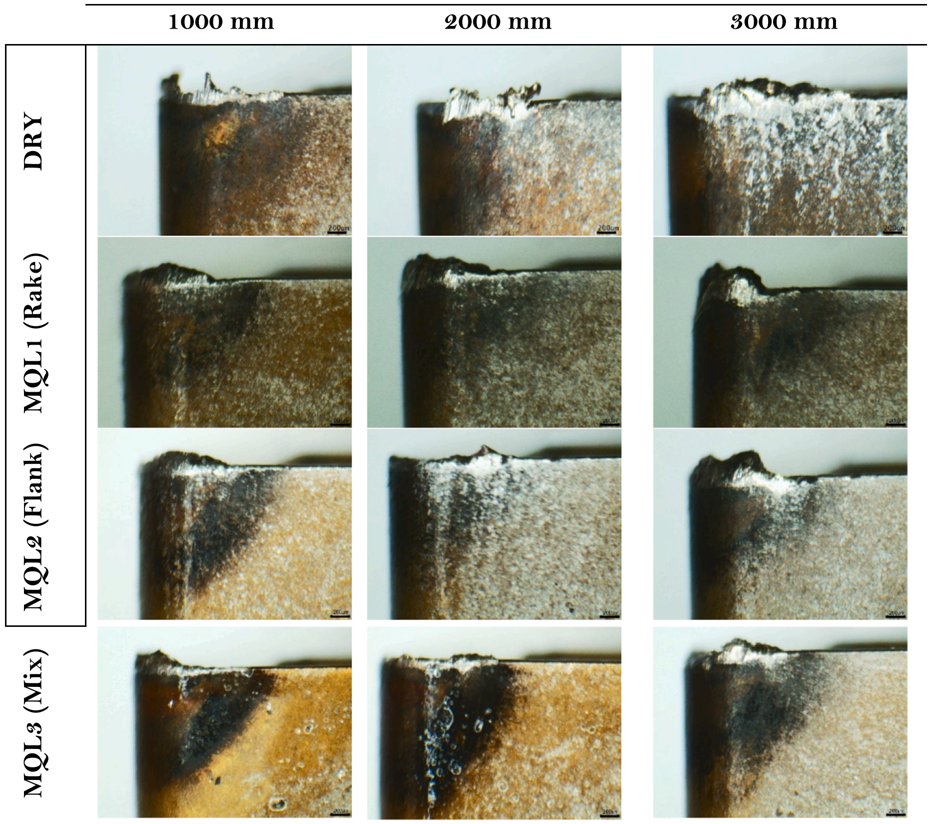
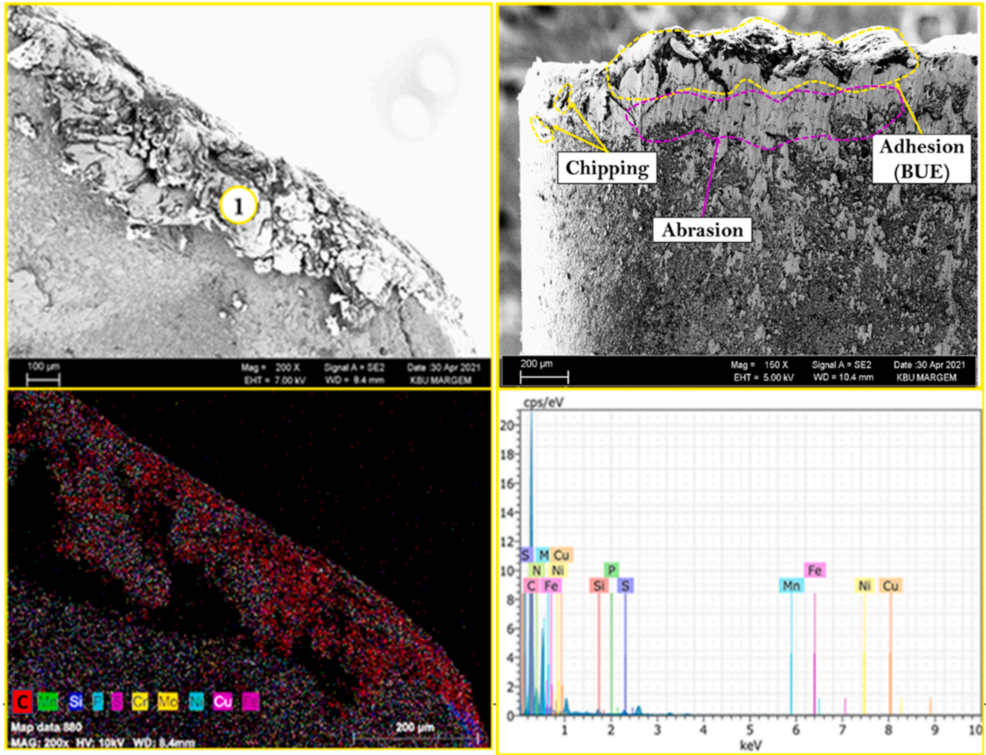


Fig. 7. Optical images of cutting tools under different conditions.

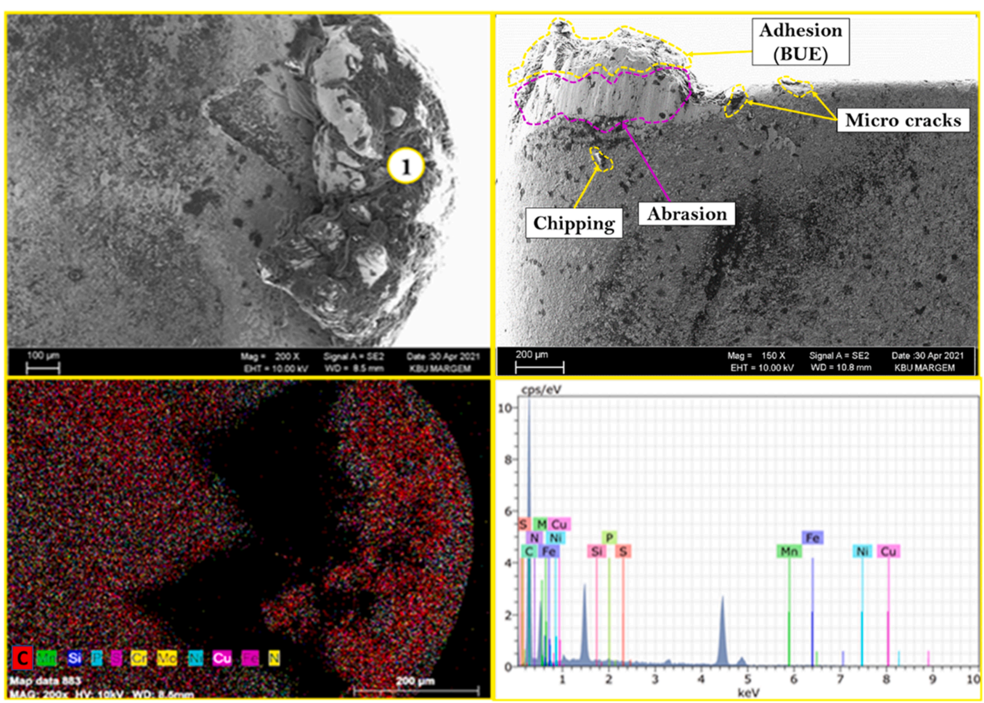
purpose. Though, the machine tool design is depended on the highest energy requirement that will occur during the machining of the material. Therefore, optimization and calculation of machining parameters for minimum energy consumption is required to be identified to fulfil the conditions of sustainable manufacturing. Fig. 4 shows the energy consumption values attained from the turning tests under various cutting environments. It can be noticed that energy consumption reveals a same results to the surface roughness values and the maximum energy consumption value was taken as 299.7 kJ under dry conditions. Comparing the application of MQL1 with the dry condition, it can be seen that the energy consumption is reduced about 11.67% and for MQL2 the reduction is 16.67% and for MQL3, the highest reduction of 23.67% has been observed. Because in dry machining with no lubricant, the required energy is the greatest to cause shear deformation and overcome friction between tool-chip interfaces. However, the use of MQL has resulted in better machining conditions, easier deformation of workpiece material, and improved chip flow, resulting in lower energy consumption. Improved lubricity at the tool-work and chip-tool interfaces reduced energy consumption during MQL machining, especially MQL3 application. It can be entirely said that lubricants used for MQL will reduce the total energy consumption by reducing the tool-workpiece contact and reducing friction. Regarding this issue, Race et al. [56] compared the cutting environments based on energy consumption in machining of SA516 steel via carbide inserts and emphasized that MQL is better than dry and flood cutting condition due to less friction and less temperature difference between tool and workpiece. Meanwhile, the dissemination of energy consumption data is shown in Fig. 5. The machining power consumed 40% energy followed by standby power, linear motor power, spindle motor power and MQL systme power, respectively. Therefore, there is a strict need to control the machining power by controlling process parameters and cutting conditions.

3.3. *Tool wear analysis*

Different wear mechanisms are observed in the wear of cutting tools during machining operations. These wear types create a certain damage onto the cutting tool based on the wear mechanisms that dominate the cutting area. The most important of these wear type is flank wear occurring at both the main cutting edge and the auxiliary cutting edge of the cutting tool. During chip removal, the actual cutting action occurs at the actual cutting edge and the auxiliary cutting edge determines the dimensional tolerance of the workpiece and the finished surface quality. The actual cutting edge wear consists of large cutting forces and high temperature. During machining, the temperature increases with increasing cutting speed. This is attributed to the fact that the increase in cutting speed generates the small fracture also known as chipping at the cutting tool edge and thus leads to high surface roughness values. That's why, the MQL method was employed to improve both the surface and tool properties. In this context, Szczotkarz et al. [29], Chen et al. [54], Özbek and Saruhan [57] investigated the superiority of MQL over dry condition in machining of 316L stainless steel, TiB2/7075 aluminum alloys and AISI D2 steel, respectively. They prove that the MQL conditions is very helpful to slow-down the wear of cutting tools as compared with the dry conditions. These machining studies have generally used one dimensional nozzle of lubricants and as a novelty, the lubricant in the MQL technique was sprayed to both faces of the cutting insert in the current study. The tool wear values at the cutting lengths of 1000, 2000 and 3000 mm cutting length are given in Fig. 6. The value taken as the criteria of the tool wear is 0.3 mm based on literature reviews [58,59]. The applcaition of MQL 1 condition show less tool wear than dry condition with an average reduction of 36.5%. Moreover, MQL2 conditions are better than the dry condition upto reduction of 42.9% as well as MQL1 condition. However, by comparing all cutting environments, MQL3 accomplished the least tool wear because of more homogeneous distribution of atomized lubricants between the tool and the workpiece.



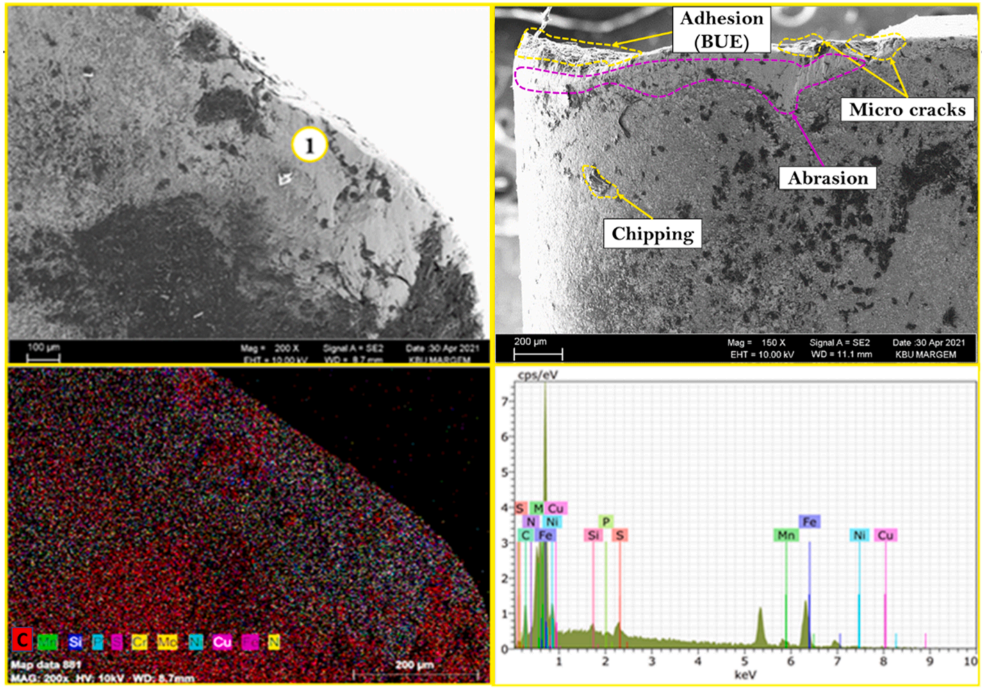
(a)



(b)

Fig. 8. SEM with EDX analysis after 3000 mm cutting length of rake face and flank face under (a) Dry condition (b) MQL1 (Rake) condition, (c) MQL2 (Flank) condition and (d) MQL3 (Rake and flank) condition.

As a result, the MQL3 achieved a less flank tool wear value of 0.15 mm. Fig. 6 also demonstrates that the tool wear values are increased with an increase in cutting length from 1000 mm to 3000 mm and this increment in wear values were noticed in all cooling conditions followed by MQL3, MQL2, MQL1 and dry conditions. In the case of MQL3 condition, the values of tool wear are increased from 111.3% and 183.1% with the change in cutting length from 1000 mm to 3000 mm, respectively. These wear amount rates have a similar tendency in all MQL applications and



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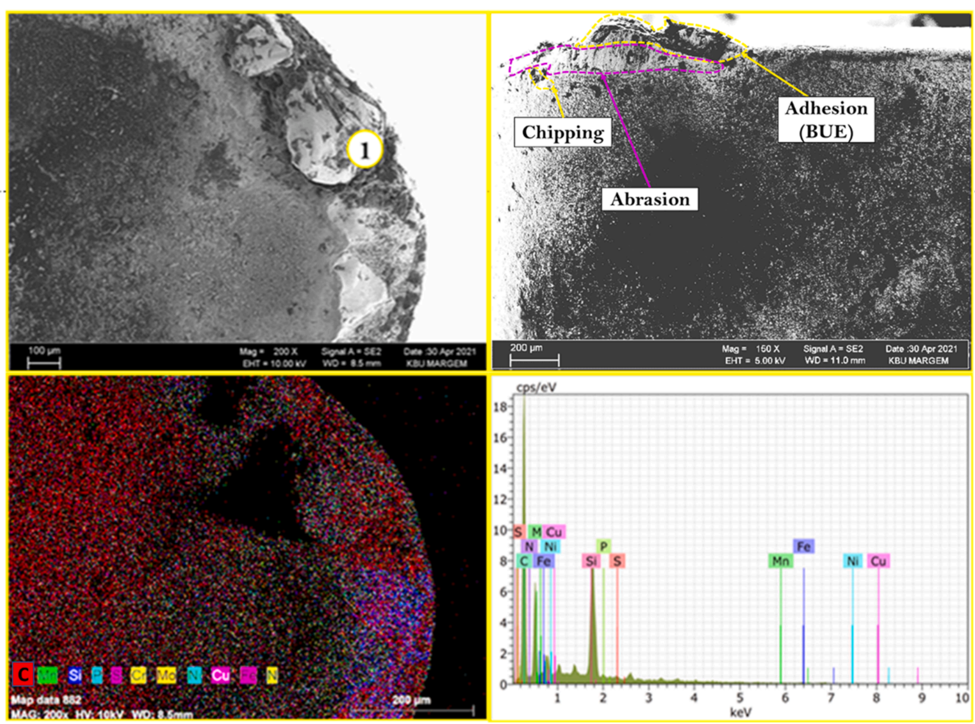

(d)

Fig. 8. (*continued*).

it can be seen from both Figs. 6 and 7. Further, these findings indicate that MQL applications, particularly the mixed MQL technique, have a significant impact on tool wear. The burning of tool with change in cooling conditions are easily observed in the optical images of Fig. 7, whereas the detailed mechanism is shown in Fig. 8. When the images in Figs. 7 and 8 are examined, it is possible to say that a certain amount of flank wear mechanism occurs in the carbide inserts as well as adhesive BUE formations. It can be said that the cutting tool tips cannot cut with the real cutting edges and the formed BUEs act as a cutting edges, thus preventing the wear on the tool cutting edges. In addition, due to the high temperature in high cutting speed machining of the 2205 duplex steel, tool wear occurred prominently in dry conditions. Therefore, it can be stated that one directional MQL1 and MQL2 gave better performance in terms of the tool wear by looking in Fig. 8b and 8c at the feed rate of 0.2 mm/rev and the cutting speed of 200 m/min. However, the most effective method was indicated as two directional MQL3 by

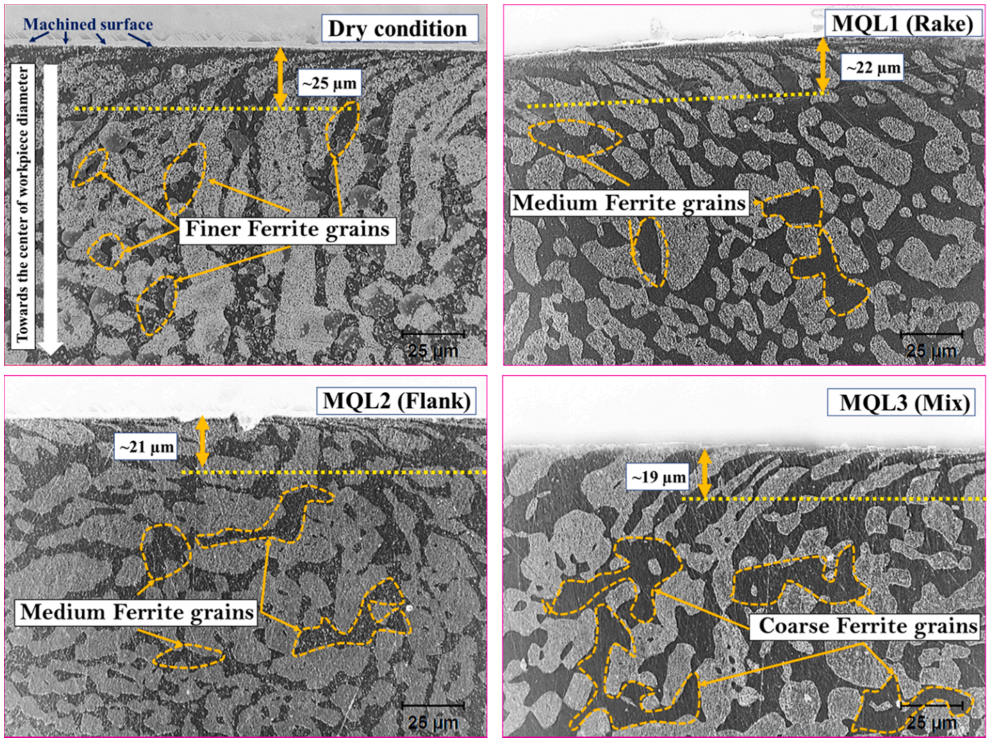

Fig. 9. Microstructure of the machined workpieces after 3000 mm cutting length.

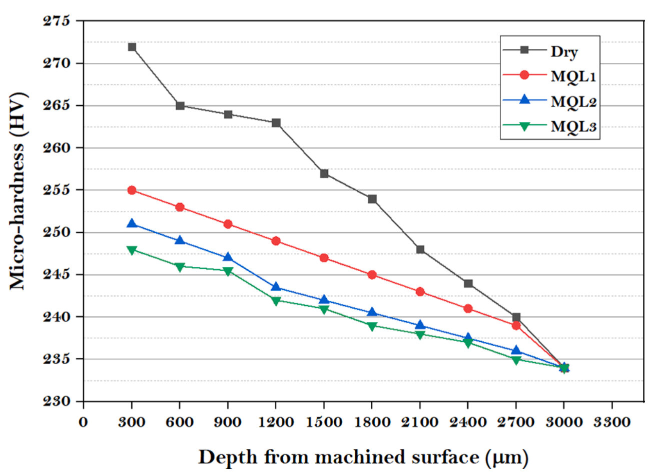

Fig. 10. Results of microhardness of the machined workpieces after 3000 mm cutting length.

obtaining the least flank wear by examining of Fig. 8d. When analyzing of EDX analysis, the formation of BUE consists of generally carbon element "C". The phenomenon of protective film of Triethanolamine based WerteMist lubricant was proved from Fig. 8 b, 8c and 8d as encountered of "N" which is main element of Triethanolamine.

3.4. Microstructure and micro-hardness of the machined surfaces

A significant amount of tool wear in a certain time caused the cutting tool to lose its cutting feature. Continuing the cutting process with the worn tool that has lost its cutting ability, causing the decreasing of the surface quality. In addition, the machinability of the workpiece material can be explained by the microstructure. When the microstructure is examined (Fig. 9), ferrite (black ones) and austenite (white ones) grains are seen in the workpiece material. The ferrite grains are soft and ductile, and they are included less in the machined material under the dry condition. This means that the material has its higher hardness form since less ferrite (higher austenite) indicates harder form. While austenite is high-temperature phase of stainless steels, it can be mostly included if the material is exposed to high temperature occurred in dry turning. The grain sizes of the ferrites increased with MQL1, MQL2 and MQL3, respectively (Fig. 9). According to Fig. 9, the affected depth on the machined surface was influenced by the cutting parameters. The transition from dry to MQL conditions resulted in a relatively deeper alteration of the microstructure. The increase in affected depth could be attributed to an expanding area in the machined surface where the temperature surpassed the austenitization temperature, allowing for subsequent quenching via lubrication effect. The higher temperature rises around the insert edge tip caused thermal softening in the workpiece material to be localized [60].

The microhardness measurement indicated that the affected layers were significantly related to the additional tempering during machining, resulting in a lower hardness. Because the temperature was not high enough at this distance from the surface for phase transformation of the material, and the cooling time was longer, a tempering effect was produced. The microhardness of the machined surfaces has coherence with microstructure such that the workpiece machined in the dry conditions have higher hardness while the MQL conditions have less hardness (Fig. 10). Because the ferrite grains increased with MQL techniques since the workpiece are subjected to high temperature as well as sudden cooling, like a heat treatment of annealing. Based on the study, Khanna et al. [1] compared the microstructures for different cooling methods, namely flood, MQL and cryogenic in turning of 15–5-PH stainless steel and Marques et al. [53] investigated the microstructure of the machined workpieces after MQL methods in turning of Inconel 718 alloy. The authors realized that MQL has coarser grains than dry turning and for that reason, the workpieces machined by MQL is softer than that of machined by dry condition as mentioned of our study.

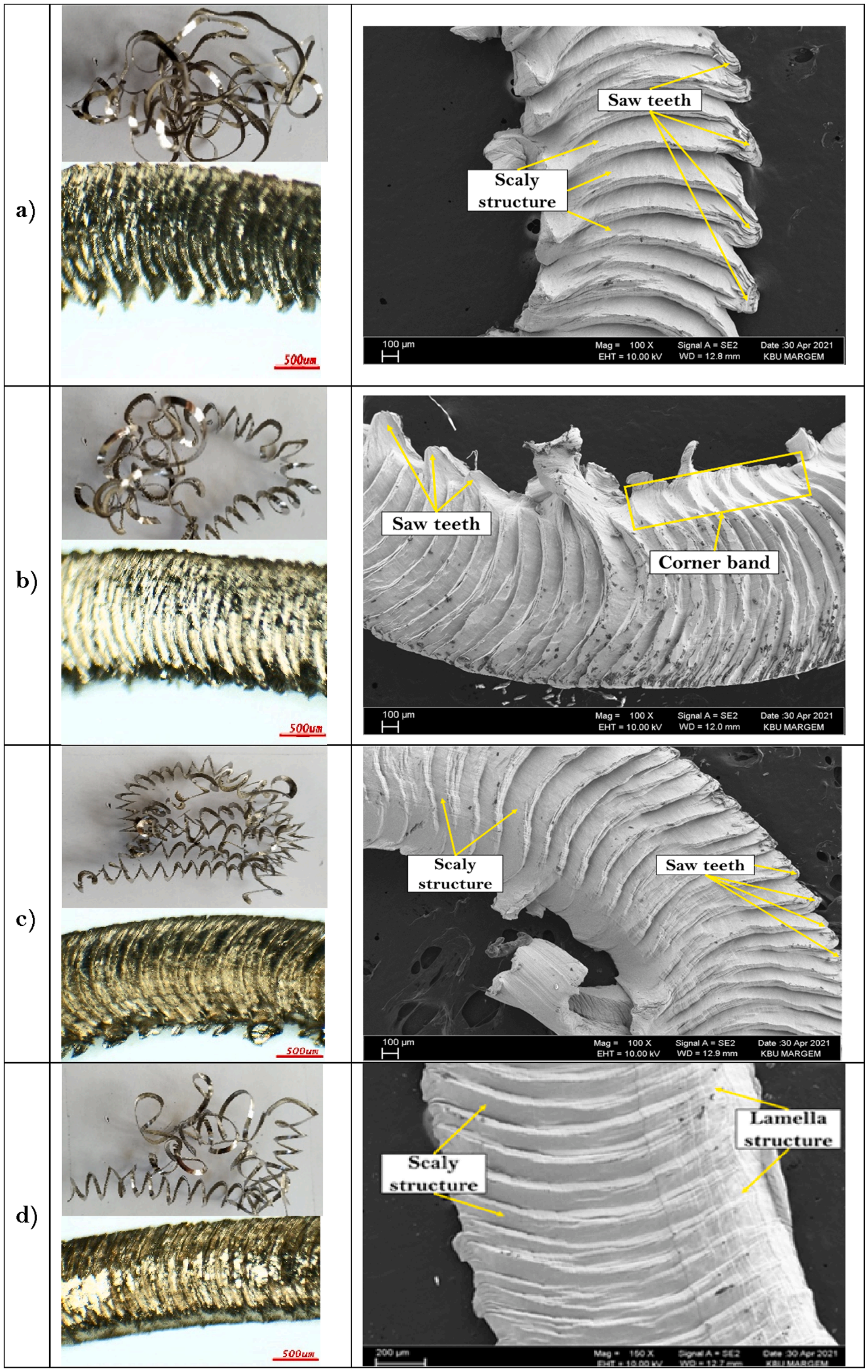

Fig. 11. Optical microscope and SEM images of removed chip after 3000 mm cutting length. a) Dry; b) MQL1 (Rake); c) MQL2 (Flank); d) MQL3 (Mix).

3.5. Chip morphology

Chip formation is the prominent machining indices that significantly affects the machining performance and causes a high energy consumption in machining. Thus, by measuring the conversion of the workpiece into chips and the flow behaviour from the surface of the inserts, it can identify the difficulties associated with process costs and tool performance. After the machining experiments, the chip generation mechanism is attempted to be discovered. According to Fig. 11, MQL methods, especially MQL3 improves chip thickness ratio by reducing chip thickness when compared to the dry condition like holistic work of Rahman et al. [61]. This means that using MQL reduces the resistance to cut, resulting in less energy consumption mentioned in Section 3.2. Another important aspect of chip morphology is shape of the chips produced during machining and it is also investigated in this work. In Fig. 11, different shapes of chips like continues, small, curly etc. were produced. Generally, continues chips are not acceptable because they directly affect the surface finish of workpiece material and the same phenomena

of continues chip is observed in dry conditions. Similarly, the MQL conditions help to break the chips into small pieces and as a result good surface finishing was observed. Fig. 11 shows the chip shapes and in MQL 3 conditions, acceptable form of chips were produced due to dual effect of MQL nozzles. Moreover, the chip removal employing carbide tools led to large pitch chip via good saw on one-side, in dry turning conditions. The same mechanism was observed by Gupta and Sood [62] in the machining of titanium and Inconel alloys. Fig. 11a show the scaly structure of chips under dry turning conditions. In contrast, the formation of teeth on the chip can also be seen in Fig. 11b, 11c and 11d for MQL1, MQL2, MQL3 machining, respectively. Though, the degree of these tooth is not clear in dry environment, this means that MQL technology facilitates the removal of chips with a reduced coefficient of friction at the tool-workpiece interaction area. Therefore, the removed chips become smooth in the MQL turning. Consequently, significant changes were observed depending on the shape of the chip by machining with a carbide tool. The wear and workpiece characteristics determined the adhesive wear mechanism. Obviously, under the influence of coating material and the multi-layer state of the cutting insert onto the duplex 2205 stainless steel, MQL technology at high cutting speed showed excellent machinability performance. In the case of MQL3 technology, there are the chips with a lamella structure that exhibits maximum machinability. There have been also lamella structured chips in MQL machining of other engineering materials like Ti6Al4V and Inconel751 alloys which is studied by Mishra et al. [63] and Balan et al. [64], respectively. The chip formed by MQL3 turning has a clear layered structure (Fig. 11d), and the machinability is improved because the MQL3 technique excessively reduced the coefficient of friction between the tool and the workpiece. Consequently, a considerable disparity was noticed depending on the chip morphology by turning via the coated carbide tool. The adhesive wear mechanism was decisive due to the wear and the properties of the duplex stainless steel. As expected, the duplex 2205 stainless steel demonstrated excellent performance in the MQL method at high cutting speeds.

4. Conclusions

The present study investigates the tool wear, surface roughness, energy consumption, microstructure, microhardness of machined surfaces and chips morphology under two-directional MQL machining of 2205 duplex stainless steel. The important remarks from the study are summarized below.

- The surface roughness values were reduced under MQL3 conditions followed by MQL2 (flank), MQL1 (rake) and dry conditions. Similarly, less burns with smooth surface were observed under MQL 3 conditions. This is basically due to the fact that the MQL3 provides the better lubrication effect at cutting zone and as a results, less vibrations were produced during machining operations. These vibrations controlled the surface roughness values upto great extent.
- In the case of energy consumption, different cutting conditions show different results. When compared MQL1, MQL2 and MQL3 with dry condition, they consumed less energy than dry machining by approximately 20.0%, 25.0% and 32.0%, respectively. The minimum energy consumption was reached by MQL3 condition as 203.67 kJ. This is due to the phenomena that during MQL3 condition, less force is required to plough the parent material from resisting surface. This less forces is totally responsible for less energy consumption values under MQL3 conditions.
- The tool wear results also follow the same trend of surface roughness and energy consumption values. That means the tool wear i.e., flank wear values are less in the case of MQL3 conditions as compared with MQL2, MQL1 and dry conditions. The SEM observations also claim that the less built up edge formation with less abrasion and adhesion marks are observed under MQL3 conditions. This change in phenomena is due to the generation of high cutting temperature, fracture of cutting edge etc. under dry conditions.
- The microstructure and microhardnesss values are observed in this work. The MQL technique is responsible for increment in ferrite grains because the workpiece is exposed to high temperature besides the rapid cooling. This situation makes the machined work pieces softer than that of dry condition and less microhardness values were observed under MQL3 conditions.
- The chip analysis also provides meaningful information about the machining performance. Two type of chips i.e., short and long type chips were produced under MQL and dry conditions. In general, the short chips are favorable for machining and they are mostly produced under MQL3 conditions. This is because the application of air with cutting fluid help to break the chips into small pieces and as a result sound machining characteristics were observed under MQL3 conditions.
- The present work have some limitations but it could be considered in future for better results. The influence of different positions with the help of nano fluids is still not available in the literature. Similarly, the effect of different geometric parameters of cutting tools could be considered for future investigations.

CRediT authorship contribution statement

Munish Kumar Gupta: Investigation, Formal analysis, Conceptualization, Writing – review & editing. **Mehmet Boy:** Conceptualization, Writing – review & editing. **Mehmet Erdi Korkmaz:** Investigation, Formal analysis, Conceptualization, Writing – review & editing. **Nafiz Yaşar:** Investigation, Formal analysis, Conceptualization, Writing – review & editing. **Mustafa Günay:** Conceptualization, Writing – review & editing, Supervision. **Grzegorz M. Krolczyk:** Conceptualization, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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